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Innovative Space-Based Radar Antenna Technology (ISAT) Program

Now, I'd like to tell you about the Innovative Space-Based Radar Antenna Technology, or ISAT, Program.

When it comes to detecting faint objects with any form of electromagnetic radiation embedded in strong background clutter and noise, there is no substitute for aperture. Whether using radio frequencies, light, or infrared, the more photons that can be gathered from a target of interest, the better.

Another inescapable fact of physics is that the further away a sensor is from an object—and space can be pretty far away—the larger the collection aperture needs to be to maintain a prescribed detection and resolution performance. The narrower beamwidths enabled by large apertures also play a significant role in limiting the amount of interference emanating from other locations. The Arecibo antenna in Puerto Rico and the Hubble telescope dramatically illustrate the "bigger is better" principle.

Of course, getting extremely large apertures into space reliably and affordably is a significant challenge. In fact, it is a true "DARPA hard" problem. Modern antennas must do much more than simply gather photons.

For example, to meet the demands of rapid area coverage and high revisit rates, scanning must be performed electronically. ESAs, or electronically scanned arrays, eliminate the need for mechanical slewing, often a necessity for very large antennas.

For narrowband systems (i.e., when the signals of interest are reasonably approximated as a single frequency sine wave), electronic scanning is accomplished by introducing phase shifts between different parts or subarrays of the antenna. This is because time delay equates to a phase shift when a narrowband signal propagates across the antenna from an angle not aligned with the array boresight. Unfortunately, simple phase shifts are inadequate when wider bandwidth signals are required.

For example, synthetic aperture radar (or SAR) bandwidths can easily approach half a Gigahertz or more at X-band (3 cm wavelength). This limits phase-only electronic scanning antennas to approximately a meter or less resolution depending on how much scanning off boresight is required.

For larger antennas, the array can be divided into separate sections, each with a separate receiver and true time delay introduced between the subarrays. If the outputs of each subarray are digital, time delay is easily introduced with software. The practical consequence of a true time delay requirement for a large spaceborne antenna is increased complexity, weight, volume, and power consumption.

Before discussing the technical challenges of deploying extremely large and capable antennas in space, we need to further establish the rationale for such large apertures. A significant case in point is space-based radar, or SBR. Ideally, SBR will provide continuous surveillance of surface mobile targets via a GMTI (or ground moving target indicator) mode of operation in much the same manner as existing and future planned JSTARS and Global Hawk systems.

Consider the impact on antenna size requirements if we attempt to replicate JSTARS performance from space. A key antenna metric is resolution and accuracy. The JSTARS antenna is approximately 7 m in horizontal length. At a range of 150 km, this translates into a cross-range resolution of approximately 1000 m. The actual accuracy of the measurement is a function of signal-to-noise ratio (or SNR) and can be a factor of 10 to 20 times better than the fundamental resolution.

In a low earth orbit (or LEO) side-looking configuration, operating ranges of 1500 km are possible—a factor of 10 increase in range.

To maintain the same resolution, the antenna would need to be 57 m long. At MEO altitudes, say 10,000 km, the length increases to approximately 320 m.

Primary reasons for even considering MEO, despite the demands on antenna size, are the significantly reduced number of satellites required to achieve persistent 24/7 coverage and steeper grazing angles, alleviating terrain obscuration.

Another extremely important metric for GMTI radar is the minimum detectable velocity, or MDV, defined as the slowest radial velocity that can be separated from mainbeam ground clutter. Assuming typical cruising speeds for a Boeing 707 and 7 m length antenna, the MDV due to mainbeam clutter spread is approximately 2 m/s. To maintain this MDV at LEO requires an antenna length of approximately 100 m. The greater length is due to the increased ground speed, which translates into a greater clutter Doppler spread. Interestingly, the slower ground speeds at MEO result in a smaller antenna requirement than LEO to maintain the requisite MDV. For example at 10,000 km, an antenna of 80 m has the same MDV as the 100 m LEO.

The two primary functions of an SBR are search and track. The amount of surface area searched per unit time is set by the product of radiated power and antenna aperture area. While search capability is set by the power-aperture (PA) product, for a tracking radar PA^2 is the appropriate metric to determine how many individual tracking beams can be supported. This, in turn, implies that there is an extra benefit to increasing antenna size rather than power—doubling the antenna size quadruples tracking capability. For example, the improved resolution, accuracy, and clutter suppression of a larger antenna yield synergistic improvements in all tracking performance metrics; indeed, bigger is better.

OK, so big antennas are great for SBR. The question, of course, is how to build one that can fit into an affordable (preferably existing) launch vehicle and deploy reliably on orbit.

To answer this question, DARPA recently initiated the ISAT concept development and study program whose design goal is a tactical-grade GMTI antenna capable of functioning at either LEO (100 m class) or MEO (several hundred meter class) with a transmit aperture mass ratio of better than 5 kg/m^2—a truly DARPA hard problem.

Not surprisingly, some very new materials, technologies, and designs have emerged since conventional methods are not extensible to these demanding goals. Surprisingly some key enabling technologies already exist and have even been demonstrated in space. For example, one of the most effective ways to minimize mass and volume for launch is to utilize inflatables.

The first inflatable was a 100-ft Echo Star launched in 1960. As recently as 1996, a 14-m inflatable lenticular lens was demonstrated by the STS-77 launched from the Space Shuttle Endeavour. Although very little pressure is required to maintain shape once deployed, the presence of micrometeorite punctures necessitates the use of make-up gas. The larger the inflatable and the longer it is required to operate, the more demanding the gas reserve. This obstacle has been overcome in recent years with the development of rigidizable inflatables and other noninflatable structural elements such as shaped memory isogrids. Although many of these candidate materials have undergone extensive rad-hard testing in the lab, a remaining key milestone is their validation for reliable space operation.

The Jet Propulsion Laboratory demonstrated several inflatable truss designs in ground-based experiments. Based on these encouraging preliminary results, innovative antenna designs have emerged as scientists and engineers gain experience using these materials.

Shown in the accompanying video is a concept courtesy of L'Garde Inc, of Tustin California. Note that the highly modular and redundant design is a key feature that minimizes complexity in manufacture as well as improving reliability during deployment.

Three basic radar architectures have been identified that are potentially compatible with a large compressible truss-like backbone:

- Space-fed lens
- Space-fed cylindrical reflector
- Active lens or Active ESA (A-ESA, for short)

Of the three, the lens design is the most forgiving of unknown random distortion errors in the lens surface. The reflector is the most unforgiving and requires very careful design and manufacture. However, unlike a lens or AESA, the reflector antenna is very broadband, and can be used as an effective aperture at other lower frequencies. The AESA design has a tolerance to distortions somewhat between a lens and a reflector, but eliminates the need for a feed—a significant reduction in design complexity.

Of course, extremely lightweight and low-power T/R and amplifier modules are required to realize the AESA design. Fortunately, recent developments in so-called "RF on FLEX" and extremely low power T/R modules are making this design alternative possible.

Finally, once deployed and functional, these large antennas need to be carefully calibrated. It is no small feat to point such a narrow beam at such great distances. Fractions of an arc-second error can translate into large miss distances on the surface. Here again, some innovative concepts have been identified that take advantage of the dynamic nature of the satellite orbits. Ground beacons placed in friendly territories can provide the essential "truth signals" required to precisely calibrate the antenna array manifold.

In MEO orbits, we can expect a ground beacon to always be in the radar's field of regard.

In summary, the development of large tactical-grade ESA antennas in support of SBR is a true DARPA hard problem, one that challenges the imagination, innovation and skill of our leading scientists and engineers. Yet, if accomplished, it will provide a highly transformative intelligence, surveillance, and reconnaissance capability.

Thank you for your attention. We welcome your thoughts, comments, and most of all participation in this endeavor.